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Investigation of the characteristics of interband resonant tunnelling diodes with modified barriers

I. Lapushkin†, *A. Zakharova*† and V. Gergel‡

† Institute of Physics and Technology of the Russian Academy of Sciences, Nakhimovskii Avenue 34, Moscow 117218, Russia

‡ Institute of Radioengineering and Electronics of the Russian Academy of Sciences, Mokhovaya Str. 11, Moscow 103907, Russia

Resonant tunnelling structures (RTS) with type II heterojunctions made from InAs, AlSb, GaSb materials have been intensively studied for the last ten years experimentally and theoretically (see, for example, [1–4]). These RTS which operation is based on the overlapping of the InAs conduction band and GaSb valence band exhibit negative differential resistance (NDR) with high values of peak-to-valley (P/V) current ratio and can be useful for practical applications. Especially high values of P/V current ratio (20 at room temperature and 88 at liquid nitrogen temperature [1]) were achieved for InAs/AlSb/GaSb RTS in which the electrons from InAs contact layer heavily doped by donors tunnel through the quasibound states in the valence band quantum well of the GaSb layer into the states in the conduction band of the second InAs contact layer. Several modifications of this structure were considered to enlarge the value of P/V current ratio. The utilization of the strained GaAsSb layer instead of the GaSb quantum well layer or the inserting the AlAs monolayers into the structure [2, 3] results in increasing the P/V current ratio. In this paper we propose a modification of an InAs/AlSb/GaSb RTS, which implies the replacing the AlSb barriers by AlGaSb barriers. We show that this modification can significantly enlarge the values of P/V current ratio.

Our consideration of the InAs/AlSb/GaSb and InAs/AlGaSb/GaSb RTS is based on the model for self-consistent calculation of the I–V characteristics of these diodes, proposed in [4], where the theoretical I–V characteristics of realistic InAs/AlSb/GaSb RTS were investigated and good quantitative agreement with the experiment was achieved for the values of peak and valley current density for the first time. The only difference from the model described in [4] consists in the method of the resonant tunnelling current calculation. Here the resonant interband tunnelling current through the light hole states in the well is obtained in terms of the tunnelling probability, while in [4] this current component is obtained in terms of tunnelling times using the transfer Hamiltonian approach. The calculated conduction and valence band diagram of the InAs/AlGaSb/GaSb RTS is shown in Fig. 1.

The I–V characteristics of the symmetrical InAs/AlSb/GaSb and InAs/$Al_{0.4}Ga_{0.6}Sb$/-GaSb RTS with 25 Å wide-gap barrier layers made from AlSb and AlGaSb, respectively, and 65 Å quantum wells made from GaSb at room temperature are shown in Fig. 2. The other parameters of the InAs/AlSb/GaSb RTS are as in [1]. Curves 1 and 2 correspond to the InAs/AlSb/GaSb and InAs/AlGaSb/GaSb RTS, respectively. The InAs/AlGaSb/-GaSb RTS includes two InAs contact layers doped by donors with the concentration equal 2×10^{18} cm^{-3} and two 100 Å lightly doped spacer layers with the donor concentration equal 2×10^{16} cm^{-3}. The value of the peak current density for the InAs/AlSb/GaSb RTS is in a reasonable quantitative agreement with the experiment [1]: the calculated and measured values are approximately equal to 10^3 A/cm^2 and 200 A/cm^2, respectively.

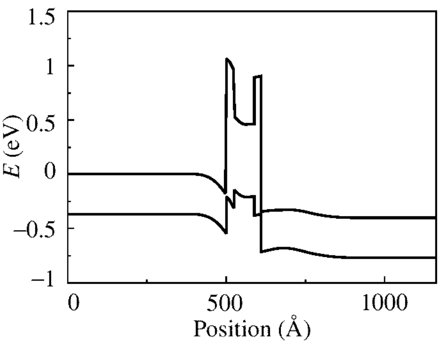

Fig. 1.

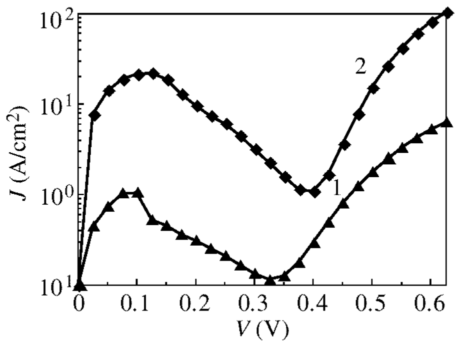

Fig. 2.

Excellent agreement with the experimental results is obtained for the value of P/V current ratio: the theoretical value is equal to 9, while the observed value equals 9.5 [1]. The calculated peak current density and P/V current ratio for the InAs/AlGaSb/GaSb RTS are about 2×10^4 A/cm^2 and 20, respectively, that are essentially greater than those for the InAs/AlSb/GaSb RTS.

The total tunnelling current density for each curve shown in Fig. 2 is the sum of different interband and intraband tunnelling current components as described in [4]. The interband tunnelling current components through the light and heavy hole states in the well make a contribution to the peak current density. The valley current is conditioned by the interband tunnelling processes through the heavy hole states in the valence band quantum well, interband tunnelling from the light hole states in the well which become lower than the conduction band edge of the left spacer near the barrier and intraband tunnelling from the states in the valence band of the left contact or spacer layer into the states in the GaSb quantum well. For high values of the external bias, only two current components are significant: the hole intraband tunnelling current and the interband tunnelling current from the light hole states in the well which are lower than the conduction band edge of emitter. The energy gap of the $Al_xGa_{1-x}Sb$ material is less than that of the AlSb. For this reason the transparency of the $Al_xGa_{1-x}Sb$ barriers is greater than that of the AlSb barriers. For this reason the current density increases with x decreasing. The peak current density enlarges greater than the valley current density, that results in the increasing the value of P/V current ratio.

In order to achieve high values of peak current density and P/V current ratio we investigated different symmetrical and asymmetrical InAs/$Al_xGa_{1-x}Sb$/GaSb RTS for $x \approx 0.4$ at room and liquid nitrogen temperature. The I-V characteristics of the RTS with 20, 25 and 30 Å left barrier, 65 Å quantum well and 20 Å right barrier at lattice temperature $T = 300$ K are shown in Fig. 3. Curves 1, 2 and 3 correspond to the diodes with 20, 25 and 30 Å left barriers, respectively. Fig. 4 represents the values of peak current density J_p (curve 1) and P/V current ratio J_p/J_v (curve 2) versus the left barrier thickness d_l. The value of J_p decreases, while the value of P/V current ratio enlarges as the left barrier thickness increases. The value of peak current density as high as 42 kA/cm^2 is obtained for the InAs/AlGaSb/GaSb RTS with $d_l = 20$ Å, the corresponding value of $J_p/J_v = 12$. For the InAs/AlGaSb/GaSb RTS with $d_l = 30$ Å the values of P/V current ratio equal 35 and peak current density equal 14 kA/cm^2 are achieved. Hence the values of peak current density and P/V current ratio can be significantly enlarged due to utilization of the AlGaSb

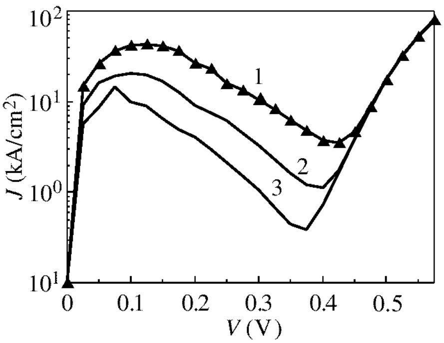

Fig. 3.

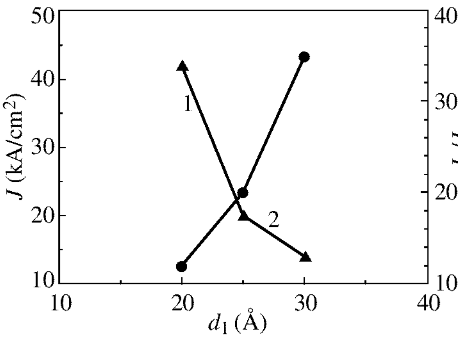

Fig. 4.

barriers instead of AlSb barriers.

The I–V characteristics of the InAs/AlGaSb/GaSb RTS with 65 Å quantum well and 20 Å right barrier at liquid nitrogen temperature are shown in Fig. 5. Curves 1, 2 and 3 represent the characteristics of the diodes with 20, 25 and 30 Å left barriers, respectively. The dependencies of the peak current density (curve 1) and P/V current ratio (curve 2) on the left barrier thickness are presented in Fig. 6. The peak current density increases only slightly with the lattice temperature decreasing. The values of J_p/J_v are much greater for the I–V curves obtained at $T = 77$ K. For the InAs/AlGaSb/GaSb RTS with $d_l = 30$ Å the P/V current ratio as high as 800 is achieved. This value is much greater than all known experimental values for RTS. The interband tunnelling current components through the light and heavy hole states in the quantum well, which compose the total tunnelling current density for the values of external bias up to the voltage corresponding to the valley current, depend slightly on the value of T. These current components drop as the voltage increases for the values of external bias greater than the voltage corresponding to the peak current density. In the NDR region the intraband tunnelling current from the states in the valence band of the left spacer or contact layer into the empty states in the valence band quantum well switches on with the voltage increases, because is lowered the hole quasi-Fermi level and increases the number of empty quasibound states in the well. This current increases with the voltage increasing that results in the observed values of valley current. The hole intraband tunnelling current drops exponentially with the temperature decreasing since decreases exponentially the number of empty states below the hole quasi-Fermi level in the GaSb quantum well. For this reason the hole intraband tunnelling current switches on at considerably greater values of external bias at $T = 77$ K than those at $T = 300$ K. This results in the increase of P/V current ratio.

Note that if the interband resonant tunnelling current through the light hole states in the well is obtained in terms of tunnelling times as in Ref. [4] the calculated values of P/V current ratio at $T = 77$ K are much greater than those shown in Fig. 6. This is due to the fact that in this case the tunnelling current through the light hole states drops to zero when the quasibound state level becomes lower than the conduction band edge of the left spacer layer near the barrier. For this reason in all calculations of the I–V characteristics in this paper the resonant tunnelling current was obtained in terms of the tunnelling probability. We believe that the phonon-assisted processes can not enlarge considerably the values of valley current and reduce the values of P/V current ratio for the investigated RTS with sufficiently thin barrier layers. In the region of valley current the phonon-assisted interband tunnelling

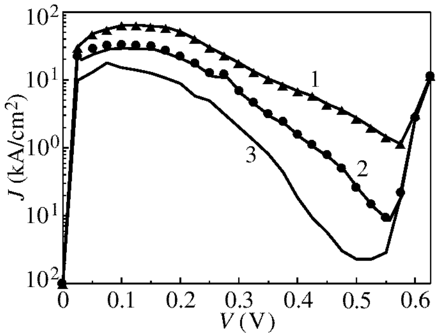

Fig. 5.

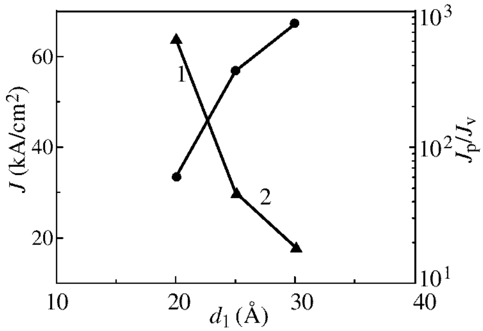

Fig. 6.

into the light hole quasibound states in the quantum well are forbidden, because all these states are below the conduction band edge of the left spacer layer near the barrier. Only the phonon-assisted interband tunnelling processes into the heavy hole states in the well can occur. These processes are not dominant, because the interband tunnelling processes without scattering are not forbidden. The phonon-assisted processes in this case can be dominant for interband transitions from the InAs conduction band into the states in the valence band of GaSb, if the thickness of the AlGaSb barrier layer is greater than 100 Å (see [5]).

In summary, we investigated theoretically the I-V characteristics of the InAs/AlSb/GaSb and InAs/AlGaSb/GaSb RTS at room and liquid nitrogen temperature. It was shown that the values of the peak current density and P/V current ratio can be essentially enlarged by employing AlGaSb barriers instead of AlSb barriers. For the InAs/AlGaSb/GaSb RTS the values of P/V current ratio greater than all until now known experimental values for RTS were obtained.

Acknowledgements

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References

[1] J. R. Södestr, D. H. Chow and T. C. McGill, *Appl. Phys. Lett.* **55**, 1094 (1989).
[2] J. N. Schulman, D. H. Chow and T. C. Hasenberg, *Solid-St. Electron.* **37**, 981 (1994).
[3] S. Tehrani, J. Shen, H. Goronkin, M. Hoogstra and T. X. Zhu, *Inst. Conf.* Ser. **136**, 209 (1994).
[4] I. Lapushkin, A. Zakharova, V. Gergel, H. Goronkin and S. Tehrani, *J. Appl. Phys.* **82**, 2421 (1997).
[5] A. Zakharova, *J. Phys.: Condens. Matter* **9**, 4635 (1997).